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U.S. PATENT APPLICATION

for

PROCESS FOR GENERATING A SEMI-SOLID SLURRY

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CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present invention is related to applications Ser. No. 10/066,527, entitled "Semi-Solid Molding Method", filed January 31, 2002 and Ser. No. 10/422,333, entitled "Semi-Solid Molding Apparatus and Method", filed April 24, 2003, hereby incorporated by reference in their entirety.

FIELD OF THE INVENTION

[0002] The present invention is directed generally to injection molding specifically to injection molding of semi-solid metal.

BACKGROUND OF THE INVENTION

[0003] Hypereutectic alloys such as the aluminum-silicon alloy 390 contain hard primary silicon crystals which make these alloys suitable for wear applications. Typical applications in which wear resistant alloys are advantageous include engine cylinder bores and pistons, compressor bodies, and transmission components.

[0004] Conventionally, hypereutectic alloys like 390 are cast using a liquid metal casting process. Common liquid metal casting processes include die casting, gravity permanent mold casting, low pressure or counter-pressure permanent mold casting and/or sand casting. Although conventional liquid casting processes are capable of producing macroscopically attractive parts, it is difficult to control the size, morphology and distribution of the primary silicon phase of parts made by these processes.

[0005] Control of the size, morphology and distribution of the primary silicon phase is important for performance of parts. Typically, control of

these parameters is attempted either by rapid solidification alone or by a combination of artificial nucleation of silicon crystals and moderately fast solidification. Failure to control the primary silicon size and distribution typically leads to excessive tool wear during machining, less than optimum performance in wear applications and reduced mechanical properties.

[0006] Another technique which has been used to make castings of hypereutectic alloys is semi-solid injection molding. Semi-solid injection molding processes typically use either a specially treated, pre-cast billet with the appropriate microstructure or a slurry especially prepared from molten alloy in equipment external to a die-casting press. The pre-cast specially treated billet must be sawed to the appropriate length before using. The pre-casting, special treatment and need to saw the billet in the first process and the external equipment and processing required for producing the slurry in the second process result in a cost premium over many liquid injection molding processes. This cost premium has limited the commercial application of semi-solid molding processes. Further, pre-cast billet is available from a relatively few sources, is currently made only from primary alloys, and process scrap cannot be reused unless reprocessed back into a billet.

SUMMARY OF THE INVENTION

[0007] One embodiment of the present invention includes a method of making a metal part by semi-solid metal injection molding comprising combining a first solid metal portion and a second liquid metal portion in a first chamber of an injection molding machine to form a semi-solid metal slurry and injecting the semi-solid metal slurry into a mold cavity to form a molded metal part.

[0008] Another embodiment of the present invention includes a method of making a metal part by semi-solid metal injection molding comprising

providing a solid metal heat sink into a shot chamber of an injection molding machine, providing liquid metal over the heat sink to form a semi-solid metal slurry, and injecting the semi-solid metal slurry into a mold cavity to form a molded metal part.

[0009] Another embodiment of the present invention includes a method of making a metal part by semi-solid metal injection molding comprising providing a solid metal heat sink into a shot chamber of an injection molding machine, wherein the shot chamber comprises a vertically oriented shot chamber having a horizontal width that is at least two times greater than a vertical depth of melt in the chamber, providing a grain refining agent into shot chamber, providing liquid metal over the heat sink and the grain refining agent to form a semi-solid metal slurry, wherein the semi-solid slurry forms in the shot chamber with a generally globular or equiaxed primary phase microstructure without stirring the semi-solid slurry, injecting the semi-solid metal slurry from the shot chamber into a mold cavity to form a molded metal part having an appendage, removing the appendage from the molded metal part, and providing the appendage back into the shot chamber of the injection molding machine as a heat sink during a subsequent step of forming a subsequent molded metal part.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] The foregoing and other features, aspects and advantages of the present invention will become apparent from the following description, appended claims and the exemplary embodiments shown in the drawings, which are briefly described below. It should be noted that unless otherwise specified like elements have the same reference numbers.

[0011] Figure 1 is schematic illustration of an injection molding apparatus with a vertically oriented shot chamber according to one embodiment of the invention.

[0012] Figure 2 is a schematic illustration of a method of injection molding with a mold having primary and second cavities according one embodiment of the invention.

[0013] Figure 3 is a micrograph of unrefined primary silicon in a part conventionally cast from liquid.

[0014] Figure 4 is a micrograph of primary silicon in a cast part according to one embodiment of the invention.

[0015] Figures 5A and 5B are micrographs of a cast part according to a comparative example.

[0016] Figures 6A, 6B, 7A, 7B, 8A, 8B, 9 and 10 are micrographs of cast parts according to embodiments of the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0017] The present inventors have developed a process of casting semi-solid metal in which it is possible to control the size, morphology and distribution of the primary silicon phase without the cost premium associated with the conventional semi-solid injection molding. The method comprises combining a predetermined volume of solid alloy with a predetermined volume of liquid of the same alloy in an injection molding machine. The temperatures and volumes of the solid and liquid are such that a semi-solid slurry is produced in the injection molding machine. That is, the solid volume acts as a heat sink, withdrawing enough heat from the liquid volume to cause the combined volume of solid and liquid to be semi-solid.

[0018] In a first embodiment of the invention, solid and liquid portions of an alloy are introduced into a shot chamber of an injection molding machine. The latent heat of the liquid alloy is sufficient to cause the solid portion of alloy to begin to melt. However, the temperature of the liquid alloy is such that, as heat is withdrawn to melt the solid alloy, the temperature of the liquid alloy drops below the liquidus of the alloy.

Further, the volume of the solid alloy is such the temperature of the combined liquid and solid portions remains above the solidus of the alloy. Thus, the combined volume of the liquid and solid alloy remains semi-solid. Typically, the solid metal portion introduced into the shot chamber comprises 5 to 30 volume percent of the combined volume of semi-solid slurry.

[0019] In one embodiment, illustrated in Figure 1, the solid and liquid portions are introduced into a vertically oriented shot chamber 86 of an injection molding apparatus 10, such as a die casting machine or press. Any suitable apparatus may be used. For example, the injection molding apparatus 10 may comprise the apparatus described in U.S. patent applications 10/066,527, filed 1/31/02 entitled "Semi-Solid Molding Method", and 10/422,333, filed 4/24/03 entitled "Semi-Solid Molding Apparatus and Method". The apparatus 10 includes a frame 12, a clamping cylinder 30, an upper die or mold section 40, a plurality of lower die or mold sections 45, a transfer table 48, a rotatable table 68, a plurality of vertical shot sleeves 70, a metal receiving station 80, and a metal transfer station 82. A respective vertical shot chamber 86 and shot piston 88 are located in each shot sleeve 70. If desired, an apparatus with a single shot sleeve may be used instead. The shot chamber 86 preferably has a horizontal width that is at least two times greater than a vertical depth of the melt in the shot chamber 86. In other words, the shot piston 88 is raised in the shot sleeve 70 to a sufficient degree and the metal is added to the shot chamber 86 to a level such that a horizontal width of the shot chamber 86 is at least two times greater than a vertical depth of the melt in the shot chamber 86. The inventors have discovered that this scenario results in a process which promotes the formation of non-dendritic, globular primary phase in hypoeutectic alloys and reduces the grain size of the primary phase in hypereutectic alloys.

[0020] Any suitable solid metal which is to be injected into the mold cavity may be used as the heat sink. Preferably, the heat sink comprises a solid metal (i.e., pure metal or metal alloy). In one aspect of the invention, the heat sink and the liquid metal comprise the same metal or metal alloy. For example, the heat sink and the liquid metal may comprise the same aluminum alloy, such as A356, 380 and 390 alloys. In another aspect of the invention, the solid metal heat sink comprises a solid grain refining agent (such as a metal alloy grain refining agent) which is adapted to refine grains of a second metal alloy, and the liquid metal comprises the second metal alloy. For example, when the liquid metal comprises an aluminum alloy, the solid heat sink may comprise a suitable grain refining agent for that aluminum alloy. If desired, the heat sink may comprise a combination of materials, such as a grain refining agent and the same metal alloy as the liquid metal.

[0021] In one embodiment of the invention the combined volume of the liquid and solid portions of metal introduced into the shot chamber of the injection molding machine is substantially equal to the volume of the mold cavity of the casting to be produced. In this embodiment, the mold cavity includes the primary cavity (the cast part), the residual biscuit, and the gating. In another embodiment of the invention illustrated in Figure 2, the mold 100 includes a secondary cavity 104 in addition to the primary cavity 102. The secondary cavity has a volume sufficient to produce a solid alloy casting suitable for use as the solid metal portion in a subsequent injection molding operation. The secondary cavity 104 may be connected to the primary cavity 102, to the sprue, and/or to the gating.

[0022] Preferably, the secondary cavity has a surface area to volume ratio of at least 5:1. More preferably, the secondary cavity has a surface area to volume ratio of at least 10:1. Additionally, the secondary cavity may contain regions to produce spikes or fins. In this way, secondary

cavity may be used to produce a solid metal casting which more easily melts than an ingot.

[0023] In another preferred embodiment of the invention, a grain refining agent is added to the shot chamber before providing the liquid metal into the shot chamber. As discussed above, the grain refining agent may comprise the whole heat sink or part of the heat sink. Preferably, the majority of the heat sink comprises an aluminum alloy and a minor part of the heat sink comprises the grain refining agent. In this embodiment of the invention the combined volume of the slurry comprising the grain refining agent, the solid metal portion (such as the aluminum alloy portion of the heat sink and any solid grain refining agent) and the liquid metal portion is substantially equal to the volume of the mold cavity. Additionally, the latent heat of the liquid metal portion is sufficient to bring a temperature of the combined volume into the semi solid state.

[0024] The grain refining agent increases the nucleation rate of new grains and thereby decreases the overall grain size of the primary phase in the slurry and the casting formed from the slurry. That is, the semi-solid slurry forms in the shot chamber with a generally small and equiaxed primary phase microstructure without stirring the semi-solid slurry. When hypoeutectic alloys are used in the method of the preferred embodiments of the present invention, these alloys contain primary alpha aluminum grains, as well as an Al-Si eutectic or another eutectic if in a non-silicon bearing alloy is used. Primary aluminum may form dendritically if not treated to form otherwise. The grain refining agent is added and the cooling rate into the semi solid temperature regime is controlled in such a way as to create a "globular" or "non-dendritic" structure. When hypereutectic alloys are used in the method of the preferred embodiments of the present invention, these alloys theoretically do not contain alpha aluminum grains, but rather only primary silicon and Al-Si eutectic.

However, because of non-equilibrium conditions alpha aluminum grains may also present. In these alloys, primary silicon is not literally "dendritic", even when it is unrefined and of large and irregular morphology. In hypereutectic alloys, the grain refiner is used to nucleate primary silicon and thus create numerous tiny (cubic) and more uniformly-sized crystals. These refined crystals are better described as uniformly sized and equiaxed due to their fairly equiaxed morphology rather than as "globular" or "non-dendritic".

[0025] In one preferred embodiment of the invention, the primary particles are dispersed uniformly throughout the slurry and uniformly throughout the casting. However, in another preferred embodiment, the primary particles are not uniformly dispersed. Thus, the casting made according to this embodiment has at least one region that is richer in primary phase than a second region of the casting.

[0026] The various embodiments of the invention herein may be practiced with a variety of metals and metal alloys. In one embodiment, the metal comprises aluminum or an aluminum alloy. The alloy may be a hypereutectic alloy, in particular a 390 alloy. If the alloy is a 390 alloy, the temperature of the semi-solid metal slurry is preferably between 505 °C and 600 °C. More preferably, the temperature of the semi-solid metal slurry is between 560 °C and 590 °C.

[0027] The preferred grain refining agent for hypereutectic aluminum alloys include phosphorous. Preferably, the grain refining agent is a phosphorus containing alloy or a phosphorous bearing salt. Preferred alloys include alloys containing copper and phosphorus, and alloys containing aluminum, copper and phosphorus. However, any suitable phosphorus containing alloy or any suitable phosphorus salt may be used.

[0028] The alloy may be a hypoeutectic alloy or a non-silicon bearing alloy, in particular an A356 alloy. If the alloy is an A356 alloy, the preferred temperature of the semi-solid metal slurry is between 560 °C

and 600 °C. More preferably, the temperature of the semi-solid metal slurry is between 575 °C and 585 °C.

[0029] The preferred grain refining agent for hypoeutectic aluminum alloys and non-silicon bearing aluminum alloys include master alloys containing titanium, boron or combinations of titanium and boron. However, any suitable grain refining agent may be used. While the A356 and 390 aluminum alloys have been mentioned, other aluminum alloys, such as the 380 alloy and various non-aluminum based alloys may also be used.

[0030] In still another preferred embodiment of the invention, the grain refining element is introduced into the liquid metal before the liquid metal is introduced into the shot chamber. In this embodiment, typically, the grain refining agent is allowed to dissolve completely into the liquid portion before the liquid portion is introduced into the shot chamber.

[0031] In another embodiment, a mold having a secondary cavity 104, discussed above, is used. In this embodiment of the invention, the grain refinement agent is placed into the secondary cavity prior to injecting the semi-solid metal into the mold cavity. Thus, the grain refinement agent is incorporated in the solid metal portion formed in the secondary cavity.

[0032] A comparison of a conventional process and an embodiment of the invention is illustrated in Figures 3 and 4. Figures 3 and 4 are micrographs which illustrate the microstructure of castings of alloy 390 (17 % Si, 4.5 % Cu, 0.5 % Mg, rest Al and impurities) made by a conventional liquid casting process without added grain refinement and a process according to an embodiment of the invention (addition of a solid Cu-8%P refining agent to the shot chamber), respectively. The conventional casting process produces a microstructure with large, irregular primary silicon crystals (dark phase). In contrast, the casting made according to an embodiment of the invention has a microstructure with smaller, more equiaxed and more uniformly sized primary silicon

crystals. A Cu 8% P rod or shot, such as a rod that is used as a brazing rod or for de-oxidation of copper alloy melts may be used as a grain refining agent. CuP dissolves at the liquidus temperature of 390 alloy or above, releasing P to form AlP crystals in the melt, and AlP then provides potent and effective nuclei for refining primary Si crystals. A preferred addition amount to accomplish small primary Si crystals is about 30 – 50 grams of CuP per 1000 grams of melt to be placed in the shot chamber (providing about 35-40 ppm of P).

[0033] Figures 5A and 5B are micrographs which illustrate the microstructure of castings of alloy 380 made by a conventional liquid casting process with no solid metal added to the shot chamber. The liquid metal was poured into the shot chamber at 585 °C and then injected into the mold cavity after a 5 second delay or dwell time in the shot chamber. Figure 5A is a micrograph of a thick section and Figure 5B is a micrograph of a thin section of a sample.

[0034] Figures 6A and 6B are micrographs which illustrate the microstructure of castings of alloy 380 where a solid piece of alloy 380 is first placed into the shot chamber of a vertical injection apparatus and then liquid metal is poured into the shot chamber at 585 °C. The semi-solid slurry is then injected into the mold cavity without a delay. The solid piece of alloy 380 comprises a gating portion snapped free from a previously cast part during the casting cycle and placed back into the shot chamber. The upper and lower dies of the mold are heated to 589 °F and 609 °F, respectively. Figure 6A is a micrograph of a thick section and Figure 6B is a micrograph of a thin section of a casting.

[0035] Figures 7A and 7B are micrographs which illustrate the microstructure of castings of alloy 390 where a solid piece of an AlCuP grain refining agent is first placed into the shot chamber of a vertical injection apparatus and then liquid metal is poured into the shot chamber. The semi-solid slurry is then injected into the mold cavity. The grain

refining agent is a proprietary AlCuP grain refining agent developed by VAW Aluminum AG in Germany and was marketed in the United States by Metallurg Inc. AlCuP already contains tiny solid crystals of AlP, thus its effect on refinement of primary Si is immediate and thorough. An appropriate amount of AlCuP to accomplish small, well distributed primary Si crystals is about 2 - 4 grams of AlCuP per about 1000 grams of melt to be placed in the shot sleeve (30 to 40 ppm of P). Figure 7A is a micrograph of a thick section and Figure 7B is a micrograph of a thin section of a casting.

[0036] Figures 8A and 8B are micrographs which illustrate the microstructure of castings of alloy 390 where a solid piece of the above mentioned AlCuP grain refining agent and a solid piece of alloy 390 removed from previously cast parts are first placed into the shot chamber of a vertical injection apparatus and then liquid metal is poured into the shot chamber. The semi-solid slurry is then injected into the mold cavity. Figure 8A is a micrograph of a thick section and Figure 8B is a micrograph of a thin section of a casting.

[0037] Figure 9 is a micrograph which illustrates the microstructure of a casting of alloy 390 where a solid piece of the above mentioned AlCuP grain refining agent grain refining agent is placed into the secondary mold cavity. The grain refining agent is incorporated in alloy 390 that is injected into the primary and secondary mold cavities. The heat sink which forms in the secondary mold cavity and which contains the grain refining agent incorporated into the alloy 390 is then broken free from the main part formed in the primary mold cavity and placed back into the shot chamber of a vertical injection apparatus. A liquid 390 metal alloy is then poured into the shot chamber over the heat sink. The semi-solid slurry is then injected into the mold containing the primary and secondary cavities. For example, for a total metal weight of 8.75 pounds in the shot chamber, the heat sink weighs 1.75 pounds (i.e., about 20

percent of the total weight). The AlCuP grain refining agent comprises about 10-12 grams of the 1.75 pound heat sink, such as a pre-cut piece of AlCuP rod which is easily dropped into the secondary mold cavity.

[0038] Without wishing to be bound by a particular theory, the present inventors believe that the heat of fusion attributable to the primary Si fraction in 390 alloy is about 15 percent of the total heat of fusion of the system. Thus, to quickly chill a quantity of 390 alloy melt from just above the liquidus to just above the eutectic temperatures involves re-melting a solid 390 alloy heat sink weighing about 20 percent of the total melt placed in the shot chamber.

[0039] Figure 10 is a micrograph which illustrates the microstructure of a casting of alloy A356 where a solid piece of alloy A356 gate post from a previous shot is first placed into the shot chamber of a vertical injection apparatus and then liquid metal is poured into the shot chamber at 610 °C so as to quickly chill it to the semi solid temperature of about 580-585 °C for casting. The semi-solid slurry is then injected into the mold cavity without a delay.

[0040] The heat sink volume and/or weight may be calculated from metal cooling curves available in metallurgy textbooks for different metal alloys. For example, the weight and/or volume of the heat sink may be selected such that when liquid metal at a temperature slightly above liquidus temperature is poured onto the heat sink forms a semi-solid slurry having a desired injection temperature in the semi-solid temperature range at a desired cooling rate. For example, the heat sink may be selected to form a semi-solid slurry at a cooling rate of 0.4 °C/sec. The preferred injection temperature varies for each alloy due to alloy composition differences.

[0041] The foregoing description of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed, and

modifications and variations are possible in light of the above teachings or may be acquired from practice of the invention. The drawings and description were chosen in order to explain the principles of the invention and its practical application. It is intended that the scope of the invention be defined by the claims appended hereto, and their equivalents.